HIGH-AVERAGE-POWER, HIGH-BRIGHTNESS ND:GLASS LASER TECHNOLOGY

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Introduction

In this report, we discuss the design and performance of a 100-J-per-pulse, solid-state laser with a repetition rate of 5 Hz resulting in an average output power of 500 W. The laser can also be operated with 10-Hz bursts of up to 50 pulses.

The system shown in Figure 1 consists of a single master oscillator and four separate amplifier chains, which are coupled by a single, stimulated Brillouin scattering (SBS), phase conjugate mirror. The laser demonstrates for the first time reliable phase locking of multiple laser amplifiers in separate optical beam lines into a single output beam with high pulse energy and high average output power. The laser has high brightness with near-diffraction-limited beam quality and, importantly, has the ability to be operated with pulse durations between 10 ns and 1 μs. The longer pulses are achieved by employing a special oscillator configuration involving amplification of the exponentially rising edge of a free-running master oscillator pulse. The shorter pulses are generated by amplifying more conventional Q-switched oscillator pulses. The laser employs zigzag laser slab technology with highly uniform pumping excitation and efficient heat extraction. In addition to providing phase locking of the individual laser beams, the SBS mirror also corrects thermally induced distortions introduced in the glass amplifier slabs. A self-pumped, Brillouin-enhanced, four-wave mixing configuration provides the nonlinear thresholds that are sufficiently low for efficient operation at the long pulse widths and prevents temporal phase fluctuations, which can interfere with the phase-locking process. The laser's high output-beam quality enables efficient second-harmonic conversion with measured full average power efficiencies that range from 65% for 500-ns pulses to more than 80% for 10-ns pulses.

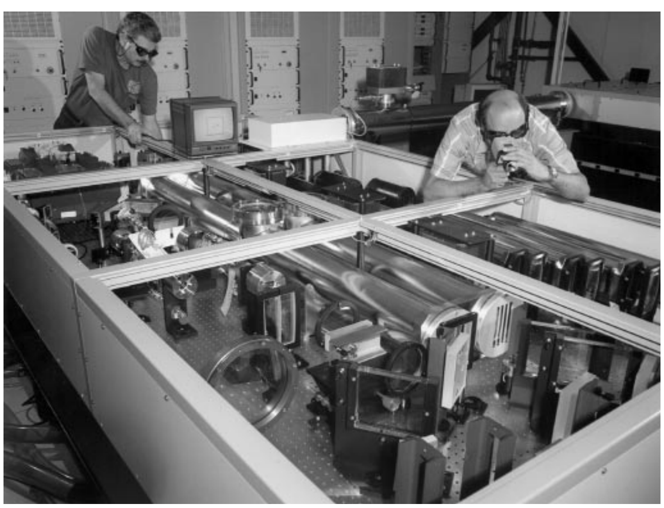

FIGURE 1. Photograph of the completed 100-J-per-pulse, four-amplifier laser system. Pictured are Jim Wintemute and Balbir Bhachu, two key contributors to the design, construction, and operation of the laser system. (70-00-0298-0151pb01)

We are developing this laser technology for several important applications. One application is to provide the U.S. Air Force with an illuminator for high-resolution imaging of space objects. Another is to provide high-rate damage testing of optics, protective coatings, and beam-blocking materials that are being developed for the National Ignition Facility (NIF). In the commercial sector, the unique high energy and high average power of the laser will enable the first high-throughput, commercial system for improving the fatigue lifetime of metals by laser shock processing.

High-Average-Power Lasers with Large Pulse Energy

Pulsed solid-state lasers with output energies exceeding 10 J have historically been limited to low repetition rates and, consequently, low average output power. Although the Nova laser can produce single pulse energies of up to 120 kJ at a wavelength of 1 µm, it is limited to firing about once every two hours for an equivalent average power of only 17 W. Commercial solid-state lasers with outputs of 10 to 100 J, when available, are generally limited to repetition rates of one shot each 20 minutes, for a maximum average power of less than 100 mW.

The thermal loading of the laser gain media is a major limitation to the available average power that can be extracted from a solid-state laser. As the repetition rate is increased, the thermal loading increases correspondingly and generates stress and strain in the gain medium. The stress and strain lead to wavefront aberrations and depolarization that can cause damage to laser optical components by distorted extraction beams as well as seriously degraded output power performance. At the upper limit of thermal loading, the gain medium will fracture. We have shown that SBS phase conjugation, which corrects the thermal aberrations of concern, can allow full-power, high-quality laser output up to the mechanical limit of the gain medium. Furthermore, SBS phase conjugation enables a practical means of increasing system output by combining multiple beams.

The single-pulse energy of the laser is limited by the physical size of the amplifier slab and the saturation fluence and optical damage threshold of the gain medium. Increasing the height of the zigzag slab quickly becomes impractical because of the cost of large optics required to accommodate the extraction beams and increased difficulty in fabricating the slab. The length of the slab is limited by the maximum gain allowed by amplified spontaneous emission (ASE) and, for short laser pulses, by the maximum glass path length allowed by nonlinear self-focusing. Increasing the zigzag slab thickness, the dimension through which cooling takes place, proportionally decreases the pulse repetition frequency. However, by phase locking multiple amplifier apertures, the pulse energy can be scaled to larger values without any compromise in repetition rate. The beams from each of the amplifiers are combined to form a single, spatially coherent beam that propagates as if it were generated in a single, diffraction-limited aperture.

Laser Architecture

The laser system architecture employs a single oscillator, the output of which is divided into four injection beams that propagate through separate amplifier chains. After being reflected from the phase conjugate mirror, the beams retrace their path through their respective amplifiers and are rejoined in the near field. The resulting output beam consists of four side-by-side beams with corrected wavefronts and with no piston phase offset between each beam. The beams therefore coherently sum in the far field, yielding a single, diffraction-limited peak.

Master Oscillator–Power Amplifier Architecture

Figure 2 shows a simplified conceptual drawing of the master oscillator–power amplifier (MOPA) architecture. The master oscillator uses a 4-mm-diameter,

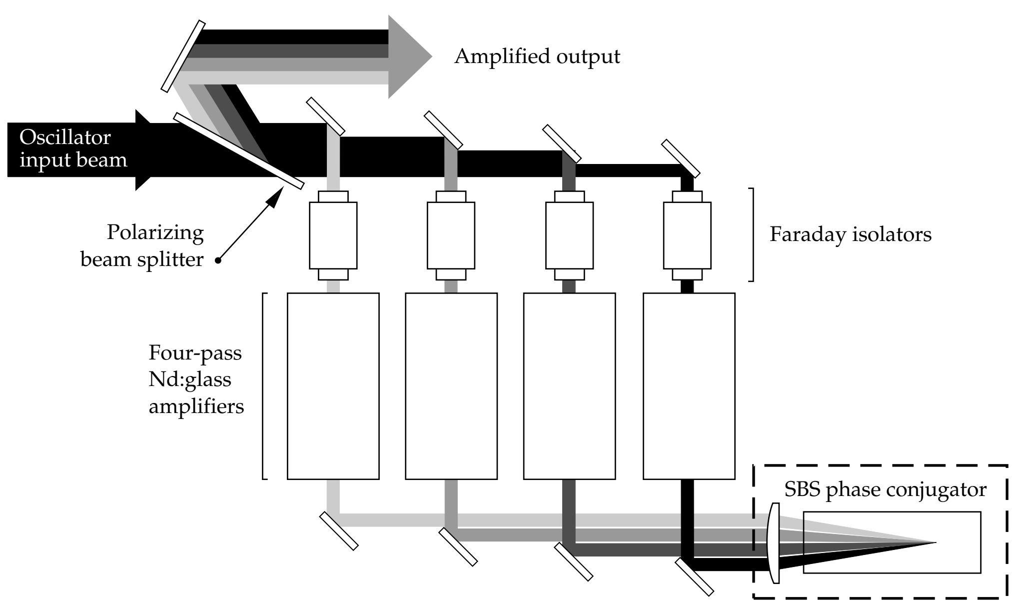

FIGURE 2. Schematic of the master oscillator–power amplifier architecture using multiple phase-locked amplifiers. Faraday rotators provide passive switching within the amplifier to allow for amplification of pulses of arbitrary duration. The SBS phase conjugator provides correction of wavefront aberrations and phase locks the multiple apertures. (70-00-0298-0152pb01)

neodymium-doped yttrium lithium fluoride (Nd:YLF) rod configured in a resonator to generate single-frequency pulses at 1.053 µm. It produces a near-diffraction-limited beam, which is then amplified to 250 mJ by two Nd:YLF preamplifiers. The output of the oscillator is sheared into four separate beams by four spatially offset mirrors. Each beam is directed into a power amplifier chain configured to provide four passes through a Nd:glass zigzag slab. At this point, the four beams are brought together side-by-side and focused into the SBS phase conjugate mirror. The phase conjugator acts on the beams such that each beam is exactly retroreflected for a reverse trip through the optical system, making four more amplifier passes. Because of its nonlinear threshold characteristics, the SBS process also provides gain isolation between the first four and second four amplification passes. The polarization rotation of the beam by large-aperture Faraday rotators in each amplifier arm isolates the counterpropagating output beam from the input, allowing it to be extracted in transmission through the injection polarizer. Figure 3 is a more detailed drawing of the laser design showing the actual beam paths in a scale layout.

Zigzag Slab Technology

Each zigzag slab amplifier consists of a rectangular slab of APG-1 Nd:glass (Schott Glass Technologies, Inc.). Each slab has dimensions of $1 \times 14 \times 40$ cm and is doped to 2.7% Nd by weight. The amplifiers have two flashlamp/reflector assemblies and appropriate plumbing to allow water cooling of the slab faces.

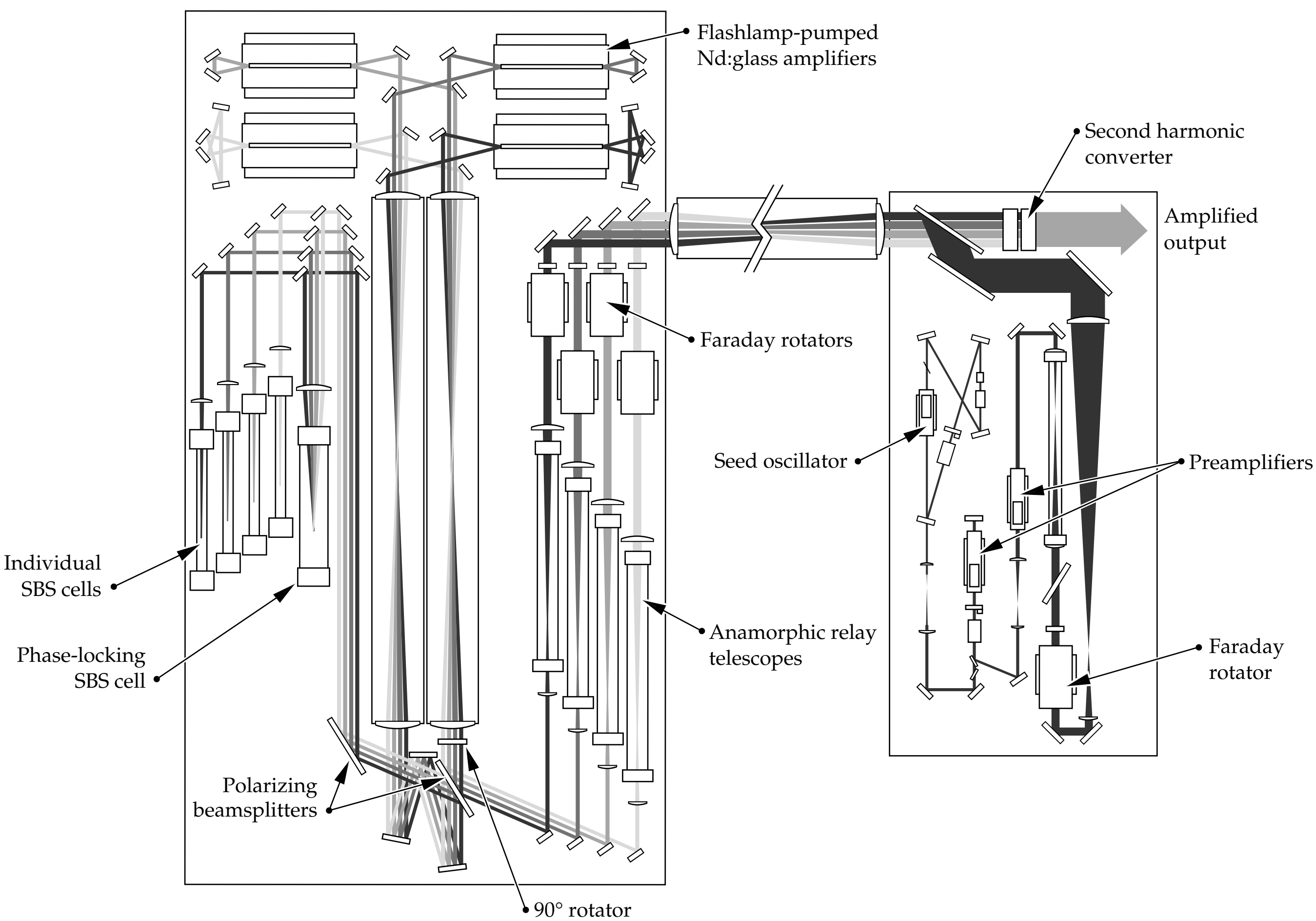

FIGURE 3. Schematic of the actual laser layout showing the master oscillator, relaying and formatting optics, power amplifiers, and phase conjugation. The system can be operated with four nonphase-locked outputs by using the individual SBS cells or, in a phase-locked mode, by combining the beams in a single conjugator cell. (70-00-0298-0153pb01)

Figure 4 is a schematic diagram of a single amplifier unit. The slab is held in the center of the assembly and has a water cooling channel along both sides, which is formed by the slab face and a reflector assembly window. Two flashlamps on each side pump the slab through the cooling channels. Diffuse reflectors surround the flashlamps. By appropriate shaping, these reflectors provide uniform optical pumping of the slab. The thin (1-cm) dimension of the glass slab provides a short path for high heat conduction from the slab center to the cooling water. The resulting heat transfer efficiently removes heat buildup in the slab and increases the repetition-rate capability of the laser. Very uniform optical pumping from the reflector assembly results in uniform energy distribution from top to bottom in the slab. At high repetition rates, the primary thermal gradient that develops in the direction of heat conduction is across the thin dimension. However, laser light propagates through a slab in a zigzag path, reflecting from side to side across the thin dimension, resulting in nearly complete cancellation of aberrations induced by the strong thermal gradient.

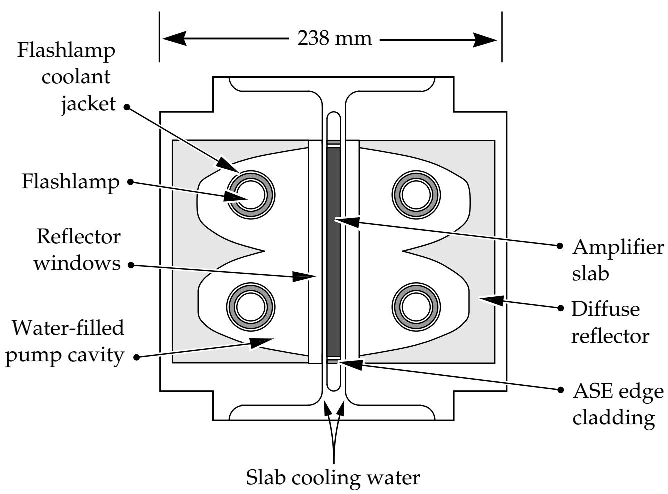

FIGURE 4. Cross-sectional view of the Nd:glass laser amplifier. Flashlamp light, tailored for highly uniform illumination by diffuse reflectors, provides the excitation to the slab. The thin (1-cm) dimension of the slab allows for efficient heat extraction into the water flow. The laser light zigzags through this thin dimension, averaging wavefront distortions. (70-00-0298-0154pb01)

Wavefront Correction with SBS Phase Conjugation

Phase conjugators are becoming widely used in high-performance, solid-state laser systems. However, there has been no previous demonstration showing that multiple beams amplified in separate optical pathways can be successfully phase locked and reliably operated at high average power. The phase locking of beams enables the scaling of pulse energy and average power output because the laser is no longer limited by the energy or thermal performance of a single-amplifier aperture. In the present case, we are able to combine the 25-J outputs of four amplifiers into a coherent, 100-J laser with four times the average power output of a single head.

As shown in Figure 5, the SBS mirror uses a Brillouin-enhanced, four-wave-mixing, loop geometry. Without such a geometry, adequate phase locking stability of the four beams cannot be achieved. The loop geometry also supports conjugation of lasers with long pulse duration or low pulse energy, where the peak power of the laser at the conjugator is below the threshold for a conventional, single-focus SBS mirror, also shown in Figure 5. The input to the SBS cell is directed through three foci in the SBS medium. The first and third foci overlap to generate a self-pumped, four-wave mixing interaction, which eliminates temporal phase instabilities and frequency drift that can lead to inadequate phase locking and spectral broadening of the laser output. The 25-J beams are rejoined in the near field to form a single beam consisting of the four, approximately square, 25-mm beams with ~1-mm interbeam gaps.

Figure 6 shows near-field intensity profiles for the four-beam set and the measured far fields for one, two, three, and four beams at full pulse energy. Phase locking of the multiple beams is clearly evident: the far-field horizontal divergence narrows with the addition of each beam, finally reaching one fourth the width of that for a single beam. The profiles are very nearly the expected Fourier transforms of the rectangular near-field patterns. The measured divergence in each case is well below 1.5 times the diffraction limit for each near-field distribution.

Technique for Long-Pulse Amplification

The extraction scheme used to generate long pulses (>200 ns) in solid-state lasers is significantly different than that normally used for short pulses. Typical Q-switched laser systems operate with pulse widths of 5 to 30 ns. Free running, long-pulse operation of a solid-state laser results in a long train of pulses caused by the phenomenon of relaxation oscillation (spiking) with only a fraction of the total energy in each subpulse. Several different approaches have been taken to solve the problem of generating long pulses, including the closed-loop variable Q-switch, the open-loop variable Q-switch, and saturable absorber Q-switches. These methods typically result in very poor pulse-to-pulse stability in pulse duration, shape, and energy, and they have only been demonstrated at low output energies.

In our high-average-power system, we amplify the

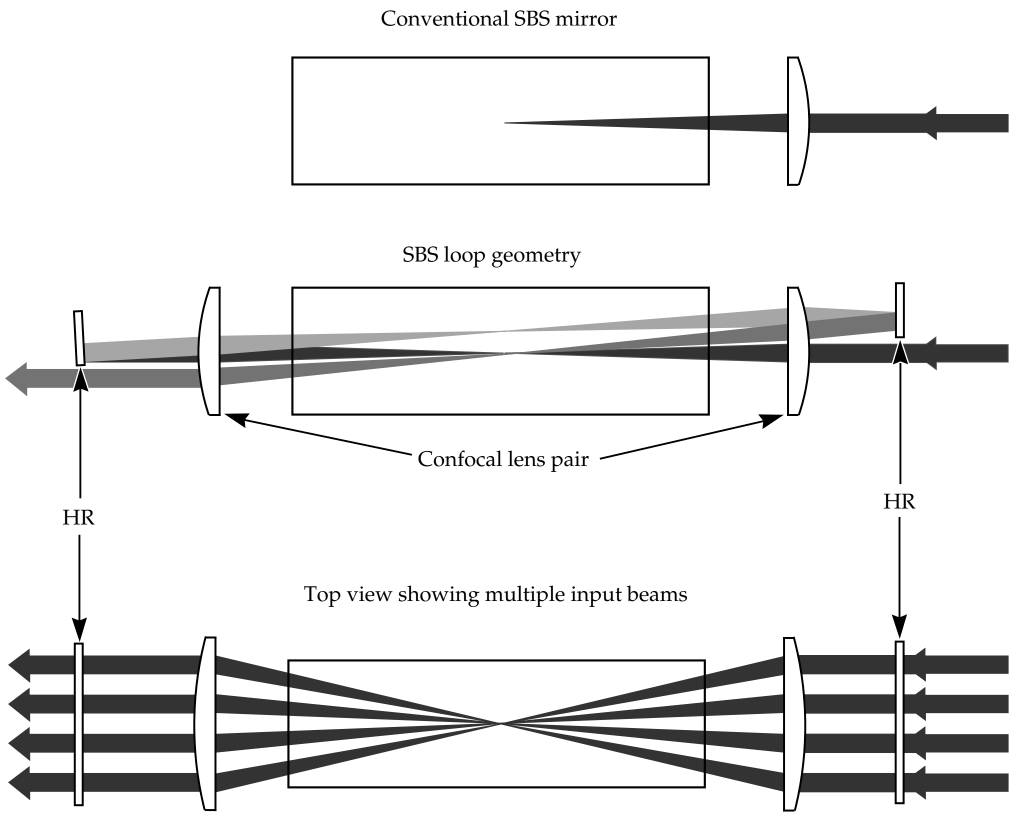

FIGURE 5. The use of an SBS loop is required to achieve high-performance phase locking of multiple apertures and narrow spectral bandwidth. This geometry (center and bottom) is compared to a conventional, single-focus, SBS phase conjugate mirror (top).
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leading edge of a free-running oscillator to produce a near-rectangular output pulse. We have recognized that by using the exponentially rising edge of the laser pulse, the amplitude of the amplified output is a function of only the exponential time constant of the oscillator buildup; therefore, increasing gain in the amplifier does not increase the peak power, but extends the length of the pulse.

In operation, the oscillator output is allowed to build up at a slow rate determined by the growth rate of the first relaxation oscillation. This initial rate is controlled by introducing a small optical loss of 5 to 10% using a Pockels cell within the oscillator cavity. Once the SBS phase conjugator in the amplifier reaches threshold, the loss is removed, increasing the buildup rate to the level required for the desired amplifier output level. This yields the lowest possible SBS threshold and generates a near-constant output power determined by the exponential time constant of the oscillator buildup.

Figure 7 shows a typical input pulse and corresponding output pulse at 600 ns. As the gain of the amplifiers is increased, the output pulse power reaches a saturated level. Further increases in output energy do not increase the peak power, but extend the pulse duration. Note that in this case, a 240-ns injection pulse is amplified to generate an output pulse with a width of 540 ns, and that the output pulse occurs well before the peak of the input pulse.

Applications

Advanced Imaging

An important application for our laser system will be its use as an illuminator for advanced imaging of space objects. LLNL is building the first 100-J, infrared (or 65-J, green), 500-ns pulse duration laser system for the U.S. Air Force. At the Starfire Optical Range, the Phillips Laboratory’s Imaging Directorate will use the device as a space object illuminator. In addition to specifications of long pulse duration and high pulse energy, the laser is required to have transform-limited coherence length. We have shown that temporal phase errors during the 500-ns pulse can be held to less than 10 milliwaves, peak to valley. In addition, the use of four separate amplifiers allows the laser to be configured with either a single phase conjugator (phase locking all beams as described here) or with up to four separate phase conjugators. By slightly shifting the pressure in the conjugator cells—hence tuning the Stokes frequency shift of the conjugated return—the frequency output of the individual amplifier channels can be offset by known and controlled amounts. Such tuning allows for imaging work involving heterodyne detection. The four-amplifier laser system will be installed at the Starfire Optical Range in early 1998.

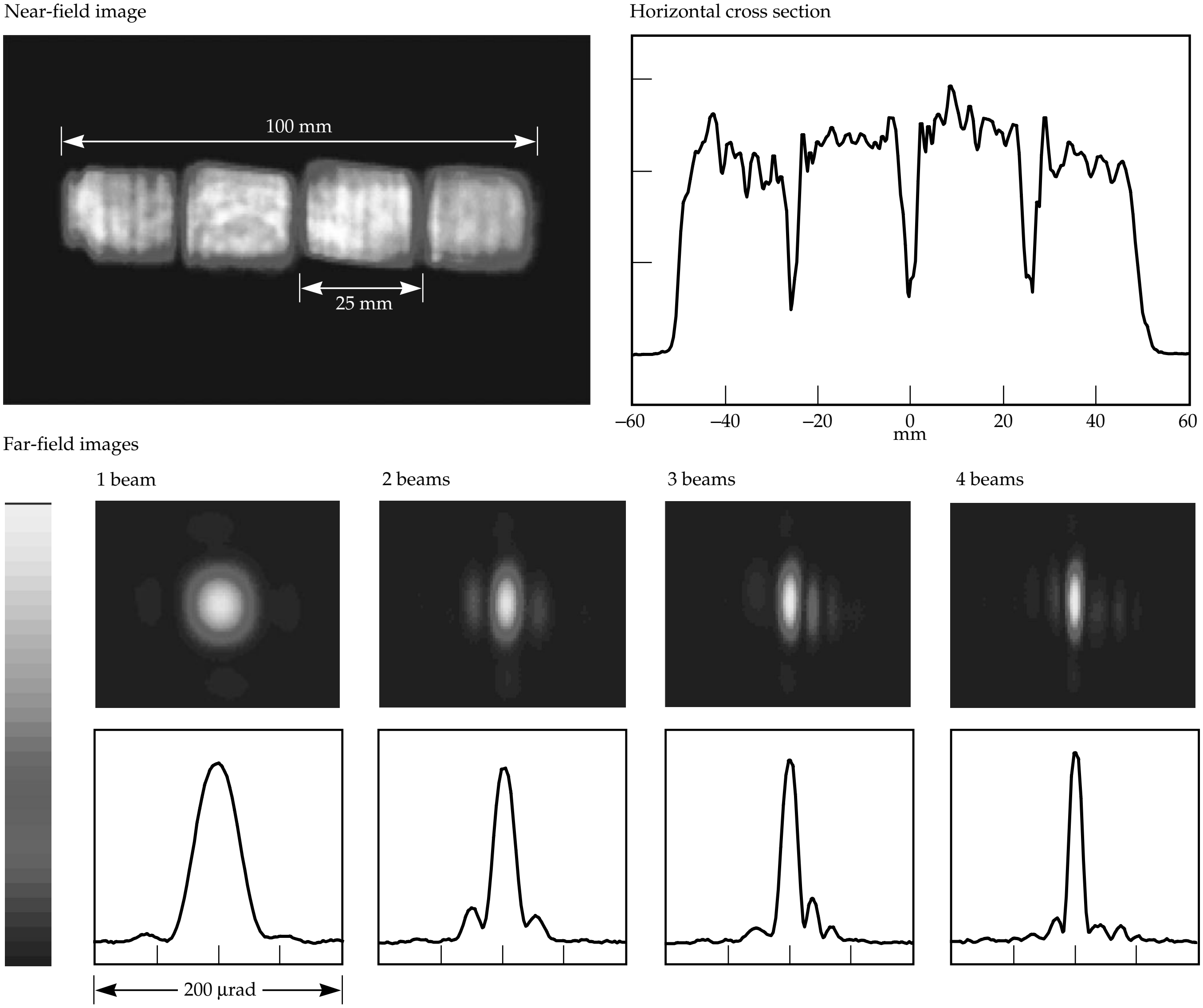

FIGURE 6. Experimental data showing the near-field beam profiles and resulting far-field laser output. The data illustrate how the far-field spot size narrows as multiple beams are phase locked using SBS phase conjugation, demonstrating excellent wavefront correction with no beam-to-beam piston phase offset errors. (70-00-0298-0156pb01)

Laser Shock Processing

Used in a 30-ns pulse width configuration, the high-energy Nd:glass laser technology described in this report is proving to be an ideal source for inducing intense and deep residual compressive stresses in metal surfaces. For some time, it has been known that controlled inducement of residual stress in a metal surface, called peening, increases the life expectancy of metal by preventing cracks arising from fatigue and corrosion. The deeper the residual stress, the better. Shocks induced with our laser have been shown to impart residual compressive stresses that are deeper and more intense than those in conventional shot peening.

In this application, our laser creates a plasma shock of 10 to 30 kbar at a metal surface. A thin layer of black paint on the metal surface provides an absorber to initiate the plasma formation and to prevent ablation of the metal. A confining or tamping material, such as a 1-mm film of water, covers the surface layer and provides an inertial barrier, which increases the intensity of the shock directed into the metal.

Figure 8 shows an x-ray diffraction measurement of the more intense and much deeper stress obtained in a titanium alloy when treated by laser shock processing in our laboratory. Deeper residual stress is important in high-stress mechanical components, such as the turbine blades of jet engines. Foreign object debris (FOD)

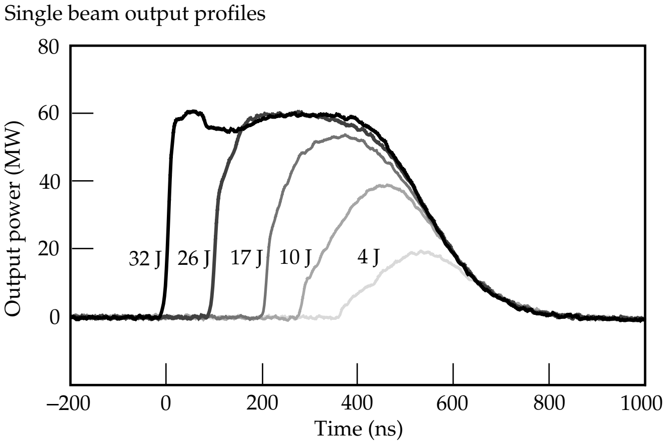

FIGURE 7. The 540-ns output pulse of the laser is generated by amplifying the exponentially rising portion of a much shorter relaxation-oscillation input pulse. The bulk of the output energy occurs well before the peak of the input. As the rise of the leading edge of the oscillator pulse falls away from exponential growth, the output pulse power falls to zero. Increases in pulse energy do not increase the output power beyond its saturation level, but result in an increased pulse duration. (70-00-0298-0157pb01)

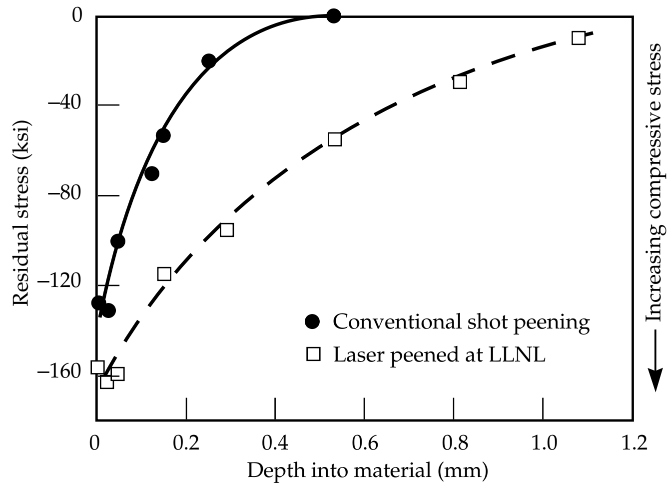

FIGURE 8. Using the high energy per pulse available from the Nd:glass laser, a more intense residual stress can be impressed into metal surfaces at a greater depth, compared to that available from conventional shot peening. (70-00-0298-0158pb01)

picked up in operation can often generate damage sites that penetrate a thinner compressive layer and, hence, become an initiation point for fatigue cracks. In testing the laser shock-processing treatment, engine blades that have deeper residual stress have been shown to exhibit significantly superior performance. However, until our recent development of high-pulse-energy, high-average-power, solid-state lasers, no system has produced both sufficient energy and repetition rate to achieve production throughput at an affordable cost. This new high-energy, high-average-power technology is expected to take laser shock processing from laboratory demonstrations into commercial production.

Summary

We have developed a class of laser system at the 100-J level with average power capability approaching 1 kW. The new technology includes uniformly pumped, zigzag slab gain media, passively switched MOPA architectures, and phase conjugation to minimize the problems associated with thermal loading. The demonstrated technique of phase locking of multiple apertures allows us to pursue new applications, such as coherent imaging and laser shock processing of materials, both of which require high pulse energies with high-average-power output.